

# Non-Orthogonal Multiple Access for Degraded Broadcast Channels: RA-CEMA

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**Abstract**—A new non-orthogonal multiple access scheme performing simultaneous transmission to multiple users characterized by different signal-to-noise ratios is proposed. Different users are multiplexed by storing their codewords into a multiplexing matrix according to properly designed patterns and then mapping the columns of the matrix onto the symbols of a higher-order constellation. At the receiver, an interference cancellation algorithm is employed in order to achieve a higher spectral efficiency than orthogonal user multiplexing. Rate-Adaptive Constellation Expansion Multiple Access (RA-CEMA) is an alternative to conventional superposition coding as a solution for transmission on the degraded broadcast channel. It combines the benefits of an increased spectral efficiency with the advantages of reusing the coding and modulation schemes already used in contemporary communication systems, thereby facilitating its adoption in standards.

## I. INTRODUCTION

Future wireless networks are expected to support significantly increased Down-Link (DL) data traffic, either in the form of an increased number of User Equipments (UEs) connected to each single DL transmitter (for example, the UEs might be sensors), or in the form of multiple, virtually concurrent data streams transmitted to the same UE (for example, where each stream is delivered to a different application running on the same UE). Both cases can be modeled as an increased number of high-rate DL data streams, which might be difficult or impossible to support using orthogonal Multiple Access (MA) schemes. The simultaneous transmission of multiple signals using some common Resource Elements (REs) is the basic feature of OverLoaded MA (OLMA) methods [1]–[3]. Practical OLMA schemes can be designed starting from different scenarios, each one characterized by a specific optimization criterion or target for the selection of transmission parameters, leading to quite different solutions. However, all OLMA schemes have to ensure reliable separation/detection and decoding of each multiplexed stream at the intended UEs.

In one scenario, the optimization target is the maximization of the aggregate DL spectral efficiency by simultaneous transmission to UEs experiencing similar physical communication channel qualities. The UEs that report to the transmitter similar Channel Quality Indicators (CQI)<sup>1</sup> are grouped into the same category, and then served by the same transmission resources

<sup>1</sup>In LTE, each UE reports Channel Quality Indicators to its serving base station. Typically, these indicators are related to the SINR experienced by the UE and are used by the scheduler to select transmission parameters.

when the instantaneous channel conditions are the best at these resources. The corresponding OLMA methods thus preserve the same data rate, the same transmitted energy per bit of each multiplexed stream, and the same scheduler design as if each of the streams would have been transmitted alone on the observed time-frequency-space resources. It further means that the transmitted power per RE is increased proportionally to the overloading factor, i.e. the number of multiplexed streams. The OLMA schemes designed using this principle include, for example, Low-Density Spread Multiple Access (LDSMA) [4]–[6], Enhanced/Turbo Trellis-Coded Multiple Access (ETCMA, TTCMA) [7], [8] and Constellation Expansion Multiple Access (CEMA) [9].

In another overloading scenario, the target is to increase the number of UEs served per RE, but without increasing the average transmitted power. The direct consequence of conserving the transmitted power is that the achievable data rates of each of multiplexed UE signals are lower than if each of them would have been transmitted separately. An additional target is to perform multiplexing in such a way that the aggregate rate of the concurrently served UEs is larger than the aggregate rate that can be obtained by time sharing (time division) multiplexing of these UEs (where each transmission interval is split into sub-intervals corresponding to different UEs). It can be shown that this target can be achieved only if the received Signal-to-Noise Ratios (SNRs) of the multiplexed UEs are not equal. It should be noted that this target is not equivalent to maximizing the aggregate data rate per RE, as it can be shown that the aggregate data rate cannot be larger than the maximum single UE data rate (obtained for the UE with the highest received SNR). Such a DL transmission to users with significantly different SNRs is known in information theory as *degraded Broadcast Channel (BC)* [10], [11].

A practical OLMA scheme for the degraded BC is based on the amplitude-weighted superposition of modulated codewords for (typically two) different UEs. UE-specific scaling coefficients are chosen with the constraint of maintaining the total transmitted power equal to the average power for single UE transmission [12]. We shall refer to such scheme as Amplitude-Weighted Non Orthogonal Multiple Access (AW-NOMA). Scaling coefficients are changed during transmission in order to make the system adaptive to the varying SNRs and data rate requirements of the served UEs.

In the case of AW-NOMA, the transmitted signal is a

series of new constellation symbols, obtained by weighted sum of two conventional modulation symbols. The minimum Euclidean Distance (ED) of the new constellation symbols might be much smaller than the ED of the corresponding conventional constellation having the same asymptotic spectral efficiency. Smaller minimum ED of AW-NOMA constellation symbols might require smaller maximum allowed distortion in the transmitter hardware than currently specified by LTE standard through the requirements on maximum Error Vector Magnitude (EVM) for each modulation format. As the EVM requirements are specifications of the minimum implementation quality of the equipment to fully achieve potential gains of each supported constellation, it follows that if NOMA constellation for some power ratio of multiplexed UEs is different from already existing LTE modulation formats, it would directly demand a new standardization effort on the specification of the corresponding EVM requirements. This standardization effort is a separate problem from the actual EVM requirements which would result from it, as it consumes significant time and resources regardless of the possibility that in some cases the NOMA EVM requirements turn out to be the same as some already existing EVM requirements. Save a side a realistic possibility that the existing LTE EVM specifications, specifying the maximum allowed signal distortion introduced by transmitter hardware to the transmitted signal, might be too loose for superposed NOMA constellation symbols.

The above potential standardization problems of AW-NOMA were the major motive to develop an alternative scheme, which we called Rate-Adaptive Constellation Expansion Multiple Access (RA-CEMA). This new scheme, which will be discussed in the sequel, performs multiplexing of several coded data streams over a multiplexing matrix matched to the size of codewords, whose columns are then mapped to symbols of an expanded conventional constellation. This scheme can be considered as a generalisation of Bit Division Multiplexing (BDM) scheme [13]<sup>2</sup>.

The paper is organized as follows: Sec. II presents the model of transmission system herein considered, Sec. III describes the proposed OLMA scheme, Sec. IV presents performance evaluation results and Sec. V draws the final conclusions.

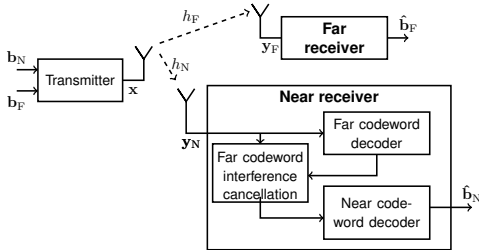


Fig. 1. System model.

<sup>2</sup>BDM is actually not an OLMA scheme, because the modulation format is fixed in advance depending on system targets such as coverage area etc., i.e. there is no scheduling. Besides, multiplexing is done similarly as in hierarchical modulation [14], within a certain number of symbols, much smaller than the codeword lengths.

## II. SYSTEM MODEL

The transmission system considered in this paper is shown in Fig. 1. It consists of a transmitter, a *far user* receiver and a *near user* receiver. The transmitter wishes to serve both users simultaneously by transmitting information words  $\mathbf{b}_N = (b_{N,0}, \dots, b_{N,K_N-1})$  and  $\mathbf{b}_F = (b_{F,0}, \dots, b_{F,K_F-1})$  with the maximum possible data rates.

The channel from transmitter to near (resp. far) receiver is modeled as a complex coefficient  $h_N$  (resp.  $h_F$ ) representing the combined effect of propagation path loss, shadow fading and fast fading. We assume that both receivers have perfect channel knowledge and that  $|h_N| > |h_F|$ .

The received signal is

$$\mathbf{y}_u = h_u \mathbf{x} + \mathbf{w}_u$$

where  $u \in \{N, F\}$  is the user index and  $\mathbf{w}_u$  is a vector representing additive white Gaussian noise (AWGN) whose elements are circularly symmetric, zero-mean *iid* Gaussian random variables with variance  $\sigma_w = N_0/2$ . Here,  $N_0$  is the two-sided power spectral density of noise.

The elements of  $\mathbf{x}$  are uniformly drawn from a unit-energy constellation and the SNR of user  $u$  is  $\rho_u = |h_u|^2/N_0$ .

## III. RA-CEMA CONCEPT

A scheme of RA-CEMA transmitter is shown in Fig. 2. In general,  $U$  UEs experiencing SNR  $\rho_u, u = 0, \dots, U-1$ , are served simultaneously using a set of Resource Blocks (RB) each consisting of a number of time-frequency REs. Each RB can be allocated for transmission to a single UE or to multiple UEs. When at least one RB is allocated to more than one UE, the MA scheme is non-orthogonal.

The RA-CEMA scheduler<sup>3</sup> obtains the CQI related to all active users and selects for concurrent transmission users characterized by different CQI values. We assume that, using this criterion, the scheduler has allocated a set of RBs, corresponding to a total number of  $G$  REs, to a pair<sup>4</sup> of UEs: a near UE characterized by a good CQI (high SNR  $\rho_N$ ), and a far UE characterized by a worse CQI (lower SNR  $\rho_F < \rho_N$ ). The channel coefficient for the near (resp. far) UE is  $h_N$  (resp.  $h_F$ ) and it is assumed to be constant over a RB.

Similarly as in LTE, using the same criteria that would be used in a conventional orthogonal MA system the RA-CEMA scheduler computes a code rate  $R_u$  and a modulation order  $m_u$  for each UE. Each information word  $\mathbf{b}_u$  is encoded by a channel coding and rate matching unit, obtaining a codeword  $\mathbf{c}_u$  consisting of  $E_u^{(0)} = m_u G$  coded bits. The total number of coded bits generated by channel coding and rate matching is therefore

$$E_{TOT} = \sum_u E_u^{(0)} = G \sum_u m_u.$$

<sup>3</sup>In each transmission interval a scheduler allocates certain time-frequency-space resources to a UE which can draw the largest benefits from these particular resources. However, the scheduler should also ensure that each UE is served within a certain predetermined delay interval.

<sup>4</sup>In general, RBs can be allocated to more than two UEs. Here, for the sake of clarity, we will consider the two-UE case.

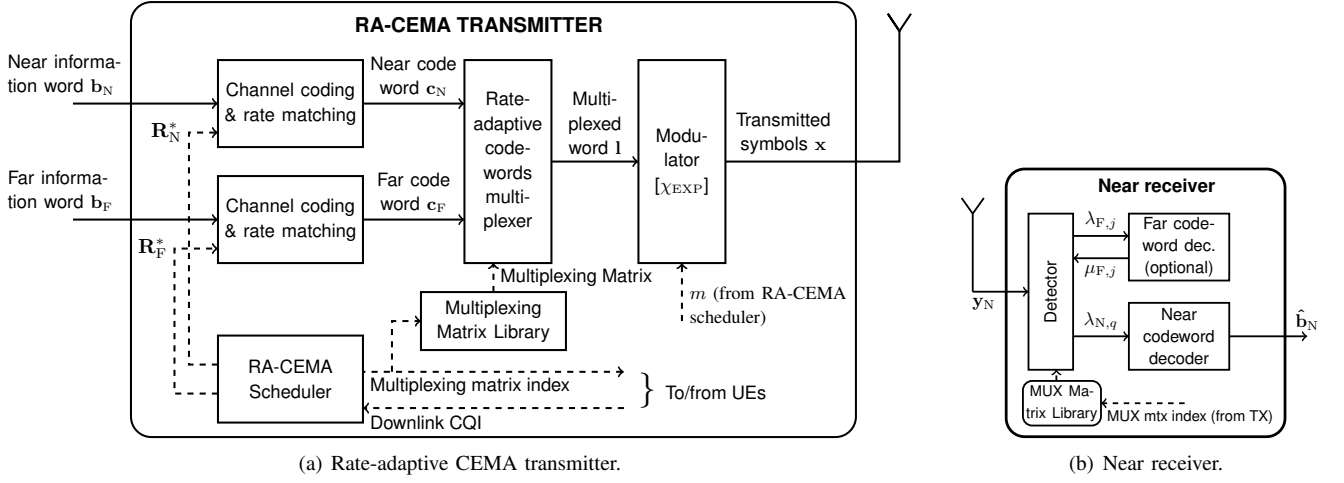


Fig. 2. Rate-adaptive CEMA system. Solid arrows indicate data signals. Dashed arrows indicate control signals.

In order to accommodate all the  $E_{\text{TOT}}$  coded bits in the allocated REs, we apply a *constellation expansion* approach [9], which consists in increasing the order of the modulator constellation to a value

$$m = \sum_{u=0}^{U-1} m_u.$$

We obtain an *expanded constellation*  $\chi_{\text{EXP}}$  having size  $2^m$  which will be used to transmit the codewords of all UEs.

Multiplexing of codewords is performed according to a *multiplexing matrix*  $\mathbf{M}$  of size  $m \times G$  whose element  $(\mathbf{M})_{i,j} \in [0, U-1]$  indicates the UE whose coded bit is transmitted using the  $i$ th label bit of the  $j$ th constellation symbol.

After multiplexing, a vector  $\mathbf{l} = (l_0, \dots, l_{G-1})$  of  $m$ -bit labels is formed and sent to the modulator which performs a one-to-one mapping of labels onto complex constellation points thus forming the transmitted vector  $\mathbf{x}$ .

#### A. Design of the Multiplexing Matrices

On the degraded BC the near user is supposed to be able (due to its higher SNR) to perfectly decode any codeword transmitted to the far user, allowing in that way its receiver to perfectly remove the far user interfering signal. If superposition coding (SC) [10] is used, such perfect removal is made possible by allocating a larger power to the far user signal than to the near user signal, assuming that both far and near user codewords use the same number of modulation symbols.

In RA-CEMA, where the near- and far-UE codewords are multiplexed onto common modulation symbols, in general it is not feasible to set arbitrary powers to the coded bits of the multiplexed users. Thus, in order to make the transmitted signal energy of the far user larger than for the near user, we use a combination of two techniques: A) special usage of unequal bit-level capacities in the modulation constellation binary labels; and B) unequal code word lengths.

The concept of bit-level capacity has been introduced in [15] and corresponds to the mutual information of each bit in a constellation binary label. Bits occupying different positions in the label exhibit different capacities which depend on the

shape of the constellation and on the specific binary labeling. In the RA-CEMA multiplexer, each row of  $\mathbf{M}$  corresponds to a different position in the constellation label. Therefore, all bits in the same row exhibit the same bit-level capacity, whereas bits in different rows possibly exhibit different bit-level capacities. We arbitrarily choose to associate label bits with a higher capacity to the first rows of  $\mathbf{M}$  and label bits with lower capacities to other rows in non-increasing order of capacity. As a higher energy per codeword results in a higher transmission rate, assigning the label bits with higher capacities to the far-UE codeword achieves the same effect as allocating a larger power to the far-UE signal.

In orthogonal MA, all REs in a RB are allocated to only one UE. In RA-CEMA, it is still possible to have some REs entirely allocated to a single UE. However, when most of the REs in a RB are allocated to a single UE, the multiplexing scheme becomes similar to an orthogonal scheme and therefore little rate gains with respect to time sharing are expected. We conclude that, by minimizing the number of REs allocated to a single UE, we obtain MA schemes with higher gains.

In summary, the multiplexing matrix is designed according to the following principles:

- 1) Assign label bits with higher capacity to the far-UE codeword.
- 2) Maximize the number of REs having their label bits assigned to multiple UE codewords.

An example of multiplexing matrix designed according to these principles is

$$\mathbf{M} = \begin{bmatrix} F & \dots & F & F & \dots & F \\ F & \dots & F & F & \dots & F \\ F & \dots & F & N & \dots & N \\ N & \dots & N & N & \dots & N \\ N & \dots & N & N & \dots & N \\ N & \dots & N & N & \dots & N \end{bmatrix}$$

where, for the sake of clarity, user indices  $u \in \{0, 1\}$  have been replaced by tags  $\{N, F\}$ . Here the order of the expanded

constellation is  $m = 6$ , hence a constellation with size  $2^6$  like 64-QAM could be used.

For some constellations, multiple label bits are characterized by the same bit-level capacity. In  $M$ -QAM, for example, each capacity level is common to two label bits. In such cases, different multiplexing matrices might be equivalent in terms of performance. To clarify this, consider the following matrix:

$$\mathbf{M}^\dagger = \begin{bmatrix} \text{F} & \dots & \text{F} & \text{F} & \dots & \text{F} \\ \text{F} & \dots & \text{F} & \text{F} & \dots & \text{F} \\ \text{N} & \dots & \text{N} & \text{N} & \dots & \text{N} \\ \text{F} & \dots & \text{F} & \text{N} & \dots & \text{N} \\ \text{N} & \dots & \text{N} & \text{N} & \dots & \text{N} \\ \text{N} & \dots & \text{N} & \text{N} & \dots & \text{N} \end{bmatrix}.$$

When used with 64-QAM, matrices  $\mathbf{M}^\dagger$  and  $\mathbf{M}$  are equivalent because their third row and fourth row correspond to label bits characterized by the same capacity level.

In order to further enhance flexibility in controlling the transmitted signal energies of the multiplexed users, we let the *actual codeword length*  $E_F$  of the *far* user to be proportional to the targeted Spectral Efficiency (SE) of that user. For example, if the targeted SE is close to its single-user SE, then the codeword length should be almost equal to  $mG$ . On the other side, if the targeted SE of the *near* user is close to its single user SE, then the codeword length of the far user is close to zero. Different far user codeword lengths produce different multiplexing matrices.

Using the described design procedure, a concrete example of matrix library has been designed for a system with SNR values  $\rho_N = 12$  dB and  $\rho_F = 6$  dB. In this case, we have  $m_F = 2$  and  $m_N = 4$ , therefore the expanded constellation has order  $m = 6$  (64-QAM). The number of available REs is  $G = 240$  and the total number of coded bits is  $E_F + E_N = mG = 1440$ . The matrix library is given in Tab. I as the set of matrices  $\{\mathbf{M}_h\}$ ,  $h = 0, \dots, 8$ . Such library will be used later in Sec. IV for performance evaluation.

TABLE I  
PARAMETER VALUES OF THE MULTIPLEXING MATRIX LIBRARY DESIGNED FOR  $\rho_N = 12$  dB,  $\rho_F = 6$  dB AND  $G = 240$  RES.

Matrix ID	$E_F$	Matrix ID	$E_F$	Matrix ID	$E_F$
$\mathbf{M}_0$	480	$\mathbf{M}_3$	640	$\mathbf{M}_6$	80
$\mathbf{M}_1$	400	$\mathbf{M}_4$	240	$\mathbf{M}_7$	840
$\mathbf{M}_2$	320	$\mathbf{M}_5$	160	$\mathbf{M}_8$	960

### B. Optimization of Information Word Lengths

The capacity region of RA-CEMA is evaluated by using two alternative measures: the Modulation and Coding Scheme (MCS) rate and the spectral efficiency of each user. We define the MCS rate  $R_u^{(\text{MCS})}$  as

$$R_u^{(\text{MCS})} = R_u m_u = K_u / G \quad [\text{inform. bits/symbol}] \quad (1)$$

where  $R_u$  is the code rate,  $m_u$  is the modulation order and  $K_u$  is the information word length. The MCS rate is a kind of generalization of single-user code rate reflecting the impact of the modulation order to the number of information

bits transmitted per modulation symbol. The reason for, in network information theory, only the code rate  $R_u$  is used as the basic measure for defining the rate regions of multiuser channels [11] is that the modulation is typically ignored.

Using the BLock Error Rate (BLER) obtained by simulation, we estimate the spectral efficiency  $\text{SE}_u$  as

$$\text{SE}_u(K_u; \mathbf{M}) = [1 - \text{BLER}(K_u)] R_u^{(\text{MCS})} [\text{bits/s/Hz}]. \quad (2)$$

This definition of SE combines the MCS rate with BLER, reflecting in that way the degree to which a certain MCS rate is achievable. Therefore the SE may be considered a more realistic measure for determining the capacity region.

The achievable MCS rate pairs and SE pairs are obtained through two different optimization procedures. The first procedure (proc. 1) maximizes the aggregate SE defined as

$$\text{SE}_\Sigma(K_N, K_F; \mathbf{M}) = \sum_{u \in \{N, F\}} \text{SE}_u(K_u; \mathbf{M}). \quad (3)$$

Using (3), we obtain the optimum pair of information word lengths

$$(K_N^*, K_F^*) = \arg \max_{K_N, K_F} \text{SE}_\Sigma(K_N, K_F; \mathbf{M}). \quad (4)$$

The corresponding pair of rates  $(R_N^{(\text{MCS})}, R_F^{(\text{MCS})})$  or spectral efficiencies  $(\text{SE}_N, \text{SE}_F)$  are obtained from (1) and (2). The corresponding code rates are computed as  $R_N^* = K_N^* / E_N$  and  $R_F^* = K_F^* / E_F$ .

The second procedure (proc. 2) aims at maximizing the aggregate MCS rate

$$R_\Sigma^{(\text{MCS})}(K_N, K_F; \mathbf{M}) = \sum_{u \in \{N, F\}} R_u^{(\text{MCS})}(K_u; \mathbf{M})$$

subject to the link quality constraint  $\text{BLER}(K_u) < \epsilon, \forall u$ . According to this criterion, the optimal pair of information word lengths is obtained as

$$(K_N^+, K_F^+) = \arg \max_{K_N, K_F} R_\Sigma^{(\text{MCS})}(K_N, K_F; \mathbf{M}) \quad (5)$$

and the corresponding pair of SE  $(\text{SE}_N, \text{SE}_F)$  and pair of MCS rates  $(R_N^{(\text{MCS})}, R_F^{(\text{MCS})})$  are obtained from (1) and (2).

### C. Interference Cancellation (IC) receiver for RA-CEMA

The near receiver performs IC as shown in Fig. 2(b). The detector computes the log-likelihood ratios (LLRs) of symbols  $s_n$  of the expanded constellation  $\chi_{\text{EXP}}$  as

$$\lambda_{n,k} = \log \frac{P(x_k = s_n | y_{N,k})}{P(x_k = s_0 | y_{N,k})}, \quad n = 0, \dots, |\chi_{\text{EXP}}| - 1 \quad (6)$$

where  $k \in \{0, \dots, G-1\}$  is the time index,  $x_k$  is the symbol transmitted at time  $k$  and  $y_{N,k}$  is the complex sample received by the near user at time  $k$ . The detector then computes the binary LLRs of codeword  $\mathbf{c}_F = (c_{F,0}, \dots, c_{F,E_F-1})$  as

$$\begin{aligned} \lambda_{F,j} &= \log \frac{P(c_{F,j} = 1 | \mathbf{y}_N)}{P(c_{F,j} = 0 | \mathbf{y}_N)} \\ &= \max_{n: \mathcal{L}_{\xi_F(j)}(s_n) = 1}^* \lambda_{n, \omega_F(j)} - \max_{n: \mathcal{L}_{\xi_F(j)}(s_n) = 0}^* \lambda_{n, \omega_F(j)} \end{aligned} \quad (7)$$

where  $\omega_F(j) \in \{0, \dots, G-1\}$  indicates the symbol in which bit  $j$  of  $\mathbf{c}_F$  has been transmitted and  $\xi_F(j) \in \{0, \dots, m-1\}$  indicates its position in the binary label. Here,  $\mathcal{L}_\xi(s_n)$  indicates the value of bit  $\xi$  in the binary label associated to constellation symbol  $s_n$  and  $\max^*(a, b) \triangleq \log(e^a + e^b)$ .

The computed LLRs are sent to the far codeword decoder which computes updated *a-posteriori* extrinsic LLRs  $\mu_{F,j}$  of coded bits. Such updated LLRs are fed back to the detector and used as *a-priori* information of the far-codeword bits.

The detector updates the LLRs of constellation symbols as

$$\bar{\lambda}_{n,k} = \lambda_{n,k} + \sum_{i=0}^{m-1} \mathcal{L}_i(s_n) \mu_{v_{ik}, z_{ik}}$$

with  $v_{ik} \in \{N, F\}$ ,  $\mu_{N,z} \equiv 0, \forall z$  and  $z_{ik} \in [0, \dots, E_{v_{ik}} - 1]$  and computes binary LLRs of codeword  $\mathbf{c}_N$  as

$$\begin{aligned} \lambda_{N,q} &= \log \frac{P(c_{N,q} = 1 | \mathbf{y}_N)}{P(c_{N,q} = 0 | \mathbf{y}_N)} \\ &= \max_{n: \mathcal{L}_{\xi_N(q)}(s_n) = 1} \bar{\lambda}_{n, \omega_N(q)} - \max_{n: \mathcal{L}_{\xi_N(q)}(s_n) = 0} \bar{\lambda}_{n, \omega_N(q)}. \end{aligned}$$

These LLRs are sent to the near codeword decoder which computes the estimate  $\hat{\mathbf{b}}_N$ .

At the far receiver, the detector computes LLRs on the transmitted symbols  $\lambda_{N,k}$  as in (6) with  $y_{N,k}$  replaced by  $y_{F,k}$ . LLRs of the far codeword bits are computed as in (7) with  $\mathbf{y}_N$  replaced by  $\mathbf{y}_F$ . Finally, the far codeword decoder applies the code constraints and computes the estimate  $\hat{\mathbf{b}}_F$ .

The near- and the far-codeword decoders are iterative turbo decoders. They compute *a-posteriori* extrinsic LLRs of coded bits and of information bits by iterative execution of the soft-in soft-out (SISO) algorithm [16].

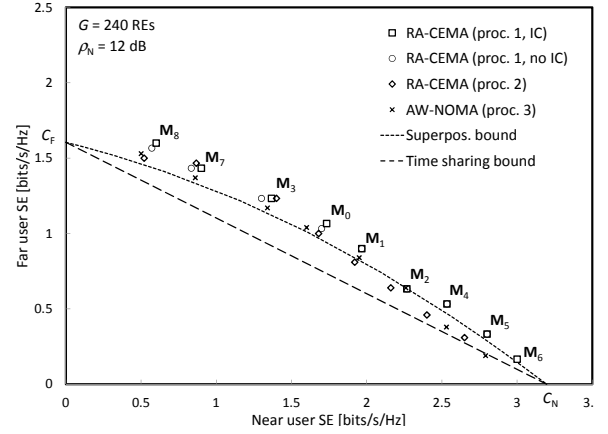
#### IV. PERFORMANCE EVALUATION

Fig. 3 shows the capacity region of RA-CEMA and of AW-NOMA on the degraded BC with AWGN obtained for two users experiencing SNRs  $\rho_N = 12$  dB and  $\rho_F = 6$  dB. The standard LTE turbo code, rate-matching scheme and QAM constellations with Gray labelling [17] have been used. In simulations, the turbo decoder performs  $N_{IT} = 10$  iterations.

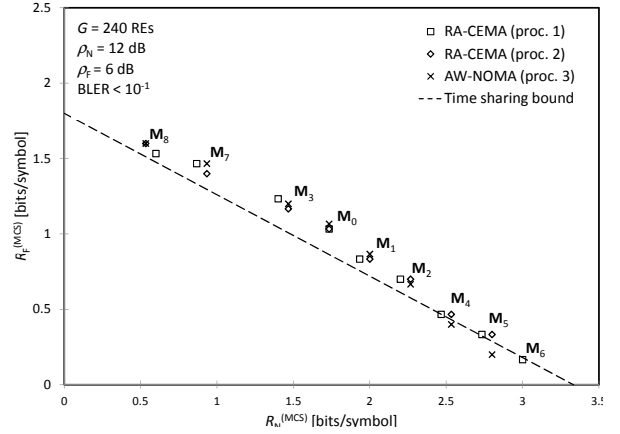
The time sharing bound corresponds to the achievable pairs of SEs or MCS rates with orthogonal multiplexing. The single-user SEs for the near UE is  $C_N = 3.2$  bits/s/Hz, while for

TABLE II  
SELECTED LTE MODULATION AND CODING SCHEMES.

Index	$m_u$	$K_u$	$R_u^{(MCS)}$	$\rho_{\min}$ [dB]	Index	$m_u$	$K_u$	$R_u^{(MCS)}$	$\rho_{\min}$ [dB]
1	2	96	0.4	-2.8	18	4	368	1.533	4.7
2	2	112	0.467	-2.1	19	4	384	1.6	5.0
3	2	128	0.533	-1.6	20	4	400	1.667	5.3
4	2	144	0.6	-1.1	21	4	416	1.733	5.5
5	2	160	0.667	-0.8	22	4	432	1.8	5.8
6	2	176	0.733	-0.3	23	4	448	1.867	6.1
7	2	192	0.8	0.2	24	4	464	1.933	6.4
8	2	208	0.867	0.7	25	4	480	2	6.6
9	2	224	0.933	1.1	26	4	512	2.133	7.1
10	2	240	1	1.5	27	4	544	2.267	7.7
11	2	256	1.067	2.0	28	4	576	2.4	8.2
12	2	272	1.133	2.3	29	4	608	2.533	8.8
13	2	288	1.2	2.8	30	4	640	2.667	9.3
14	2	304	1.267	3.2	31	4	672	2.8	9.8
15	2	320	1.333	3.6	32	4	704	2.933	10.3
16	2	336	1.4	4.0	33	4	736	3.067	10.8
17	2	352	1.467	4.4	34	4	768	3.2	11.3



(a) Spectral efficiency pairs.



(b) MCS rate pairs.

Fig. 3. Capacity region of RA-CEMA and AW-NOMA on the degraded BC with AWGN.

the far user we have  $C_F = 1.6$  bits/s/Hz). By allocating non-overlapping sub-intervals of different duration to the two users, it is possible to achieve all the rate pairs on the line connecting the points  $(C_N, 0)$  and  $(0, C_F)$ .

In Fig. 3 we also plot an approximate result labelled “Superposition bound” used to predict the achievable rate pairs based on the single-user capacities  $C_N$  and  $C_F$  achieved by the two users when transmitting alone on the AWGN channel. Applying the inverse of the AWGN capacity function  $\mathcal{C}^{-1}(y)$  (where  $y = \mathcal{C}(x) \triangleq \log_2(1 + x)$ ), we obtain

$$\tilde{\rho}_N = \mathcal{C}^{-1}(C_N) \simeq 9.15 \text{ dB}; \quad \tilde{\rho}_F = \mathcal{C}^{-1}(C_F) \simeq 3.1 \text{ dB}.$$

Finally, we apply the boundary equations of the SC rate region

$$R_N = \mathcal{C}(\alpha \tilde{\rho}_N); \quad R_F = \mathcal{C}\left(\frac{(1 - \alpha) \tilde{\rho}_F}{\alpha \tilde{\rho}_F + 1}\right)$$

where  $\alpha \in [0, 1]$  and we obtain the curve labelled “Superpos. bound” in Fig. 3. This bound fairly accurately predicts the actual boundary of the capacity region, therefore it can be considered as a useful design tool. Moreover, we observe that RA-CEMA exhibits relevant SE and rate improvements with respect to time sharing.

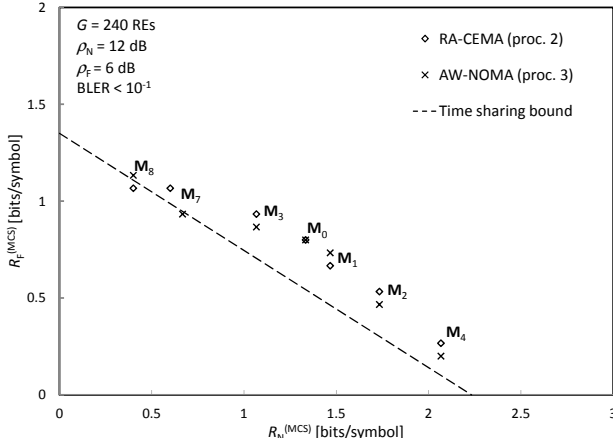


Fig. 4. Rate region of RA-CEMA and AW-NOMA on the degraded BC with block fading expressed through MCS rate pairs.

In order to compare the performance of RA-CEMA with the previously proposed AW-NOMA scheme, the optimization procedure described in [12, Sec. V-B] (denoted as “proc. 3” in Fig. 3) has been applied to determine the rate pairs corresponding to certain values of power ratios  $\alpha$  and  $(1 - \alpha)$  allocated to near and far UE respectively. However, since the MCSs therein considered are different from those used here, the step size for  $\alpha$  has been adjusted<sup>5</sup> to 0.1 dB. Tab. II shows the used MCS parameters and the SNR  $\rho_{\min}$  needed to achieve BLER below  $\epsilon = 10^{-1}$  with single-user transmission on the AWGN channel. Another set of SNR values, herein omitted for lack of space, has been obtained for the fading channel.

In Fig. 3(a), results are expressed in terms of SE pairs  $(SE_N, SE_F)$  computed using (4) and (5). Using the same two equations, the MCS rate pairs  $(R_N^{(MCS)}, R_F^{(MCS)})$  shown in Fig. 3(b) have been found. AW-NOMA SE and rate pairs are computed using the procedure mentioned above.

Fig. 3(a) also shows the SE pairs achieved when the near-user receiver does not perform IC (points labelled “RA-CEMA (proc. 1, no IC)”). RA-CEMA without IC in the near-user receiver shares some basic features of the Bit-Interleaved Coded Modulation (BICM) transmission with Gray labelling [18]. It has been observed in [13] that the label bits of BICM with Gray labelling are almost independent. From this observation it can be concluded that even the exact knowledge of the far-user coded bits should be of little help to the near-user receiver. Hence, removing IC from the near-user receiver should not make a significant deterioration of the near-user achieved SE. This conclusion has been confirmed by the simulation results in Fig. 3(a).

Similar results are shown in Fig. 4. Here, block fading with coherence time of 80 symbols (approx. equal to the size of one LTE RB) has been considered as an additional channel impairment. A channel interleaver of size  $G$  connected to the modulator output has been employed to de-correlate fading

<sup>5</sup>We observed a correlation between the step size and the “granularity” of the MCS set. In particular, the step size for  $\alpha$  should be less than the (approximate) SNR step size computed on column  $\rho_{\min}$  of Tab. II.

within each block. Also on the fading channel, both RA-CEMA and AW-NOMA perform better than time sharing.

## V. CONCLUSIONS

A new multiple access scheme for the degraded broadcast channel, which performs multiplexing of UE signals by storing their codewords into a multiplexing matrix and then maps the columns onto constellation symbols, has been proposed. The new scheme has similar performance as conventional schemes based on superposition coding while avoiding their potential standardization problems caused by the use of unconventional constellations.

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